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A. G. NEWHALL 189

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DISINFESTATION OF SOIL BY HEAT, FLOODING AND FUMIGATION

A. G. NEWHALL[1]

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INTRODUCTION

Will the capacity of our agricultural lands to produce sufficient food keep pace with our ever-growing population? Now that the frontiers have been pushed across the American continents, this Malthusian spectre is again raising its ugly head. An increase in population of approximately one per cent a year can not possibly be matched by a like increase in available new land during the next century or two, and what is brought under cultivation will be at

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ever increasing cost and of lower productivity. A considerable amount of good land is being taken out of production by the growth of cities, paved roads, airports and parking areas. The need for increasing yields and avoiding all possible losses on crop land still available is obviously of increasing importance. The more obvious insects and diseases operating above ground have received much attention, to the great benefit of agriculture, but the more obscure ones operating below ground have not been accorded the study they deserve. A review of soil sterilization and fumigation will indicate how far we have come and perhaps suggest future trends. The present discussion is arbitrarily limited to flooding and to materials and methods involving heat and volatile chemicals which disinfest soils. Chemicals which act primarily as protectants, inhibitors or repellants are excluded, since they are regarded as soil amendments, as described by Daines (1946). The line is hard to draw and complete agreement is not expected.

APPLICATION OF HEAT, AND THERMAL DEATH POINTS OF PATHOGENS

The value and simplicity of heat treatments derive from the fact that most soil-harbored plant pathogens, as well as weed seeds, have rather low thermal death points. This includes insect pests, nematodes and even many of the viruses which have inactivation temperatures below 80° C. One exception is tobacco mosaic virus which requires 92° C for ten minutes, according to Johnson (1946); another is the chrysanthemum stunt virus which will stand boiling (Brierley, 1952). The relation between duration of heat (X) and the thermal deathpoint (y) is fairly well expressed by a curve of the general form $(y-a)\sqrt{X}=b$, according to van Koot and Wiertz (1947) who found 50° C to 70° C adequate for certain Verticillia and Fusaria.

It seems likely that thermal death points in many instances are merely protein-coagulating or enzyme-inactivating temperatures. Albumens and glutamens are notably not heat-stable. Work on thermal death points has been summarized by Elliott (1930) for bacterial plant pathogens, by Newhall (1940) for a number of fungi and nematodes; and others have pointed out that pasteurizing temperatures are adequate for specific pathogens (Horsfall, 1935; Vladimirskaya, 1930; Milbrath, 1929; Pittman, 1931; Grooshevov

et al., 1940; Williams et al., 1943; Van der Want, 1948; Togashi, 1949).

DRY HEAT

Nine-tenths of the sunshine reaching the earth is absorbed as heat. According to Harrison (1944), this amount is equivalent to the energy in nearly one-half pound of coal, or about 6000 B.T.U.'s per square foot per day. That this amount of heat is actually enough to effect partial sterilization of the surface soil is entirely possible for some soils in parts of India during April and May, according to Burgess (1929). Hoshino and Godfrey (1933), in a review of the temperature relations of *Heterodera radicicola*, state that soil temperatures may go high enough to kill the larvae of this nematode to a depth of three inches at times in parts of Texas. Thus plowing three times at seven- to ten-day intervals during hot weather has been suggested as a means of control for this pest. This is effective also in the Coachella Valley of southern California where it permits a fairly clean crop of carrots to be grown, in otherwise nematode-infested soil, during at least part of the year.

The repeated observations by our early settlers that the locale of brush fires was always the best place to plant tender crops and to build seedbeds have repeatedly been confirmed by scientific investigation. Burgess (1929) states that crops are far superior in England where couch fires are started in the spring, and his tests showed that top temperatures of 63° to 82° C might be reached at a depth of four inches in such areas. Kelley and McGeorge found similar temperatures in Hawaii (1913). Kletschetoff (1930) reported observing fair control of flax sickness, due to an accumulation of fungi in the soil, in parts of Russia where vegetation in the fields was burned off before sowing. Chowdhury (1944, 1945) and Reitsma and Sloof (1950) advocate control of diseases of pan in India by burning rice straw or thatching grass over the soil repeatedly until a temperature of 60° to 65° C is reached in the first nine inches of the soil, a process requiring turning the soil and burning as many as four times. Chowdhury also recommends heating soil directly, with a flame gun (2000° F) to 75° to 82° C for a depth of six inches for control of *Sclerotium rolfsii*. Tea plants on the island of Bali today are commonly set in

soil at points where bonfires of soil and sawdust have been built (Gerald Thorne, personal communication).

Surface burning and roasting have been practiced most extensively in the burley tobacco-growing areas of the southern United States where it has been in vogue for at least 60 years to control Thielavia root rot and weed seeds. The practice spread to Italy, West Australia, South Africa, France and Yugoslavia. (Benincasa, 1902, 1907; Peglion, 1900; Cappelluti, 1902; Wuiovich, 1907; Gilbert, 1909; Scherffires, Wooley and Mahan, 1909; Scherffires and Taylor, 1911; Beinhart, 1918; Clayton and McMurtrey, 1950; Loeters and Stam, 1952).

There are over a million acres of burley tobacco grown in the United States, which, at 600 to 900 square feet of seedbed to the acre, requires 14,000 to 20,000 acres of seedbed. If these beds had to be doubled in size to get enough good plants, the cost is estimated at $4 million; so bed treatments are cheaper. When seedbeds were nestled in clearings in the woods, there was always ample brush and slashing to burn, but as woodlands became less abundant, particularly in the more northerly States, more convenient though costlier methods of eliminating weed seeds and root rots were developed. Control of root rot became more important as permanent seedbeds became more popular and rotation less common. Comparisons between surface burning or direct roasting, indirect roasting or pan firing, in which the soil is shovelled into a pan over a fire, and other treatment, such as the formaldehyde drench, various steaming devices and the use of boiling water, have shown that, in general, steaming and roasting give better results than hot water, formaldehyde or surface burning. The Wyatt tobacco bed burner, or soil roaster, on a pair of wheels is capable of treating 100 square yards a day, according to Clayton and McMurtrey (1950). These seedbed treatments are carried on between November and March. The extent to which market gardeners have gone to insure disease-free soil for potting plants and seedlings is well illustrated in the description of the Warburton, the Shewell-Cooper (1937) and numerous other vertical and horizontal ovens for roasting or baking soil over coke or coal in England (Bewley, 1926, 1929).

An interesting variation of the soil roaster was built by Viscount Elveden (1921) who heated soils in various ways. One of

these was by flaming it in a rotating drum which heated about a ton an hour to a temperature of 80° C. A similar device has recently been shown by Newhall and Schroeder (1951) to be practical in the continuous pasteurization of compost soil at the rate of two cubic yards an hour with the use of but 60 cents worth of kerosene fuel. The device is an adaptation of an aggregate heater used in road repair work and is marketed in the United States for both purposes.

In all of the roasting and direct firing methods, the presence of moisture in the soil is evidently the safeguarding factor in preventing overheating and destruction of organic matter. That some injury may be expected from the prolonged treatment recommended in England is admitted by Bewley (1947, 1950) and by others who have advocated either wetting the soil a few hours after treatment or treating soil several weeks before trying to grow plants in it. Knowledge of thermal death points and development of speedier methods of heating soils have eliminated much of the dangers from overheating. Nevertheless, where steam is available it has tended to replace roasting methods.

STEAM HEAT

Methods of applying steam were brought to their present state of efficiency chiefly by vegetable and flower growers, largely in America, in England and in Germany. The scientists, with few exceptions, observed what was going on, devised experiments for explaining the phenomenal results obtained, refined procedures, and, of course, disseminated the information. For his work in the last field, he has received a disproportionate share of the credit due many ingenious practical growers who were driven to do something to reduce losses from disease organisms, chiefly nematodes, in their soils. Steaming has two great advantages over all other methods; being non-selective, it gets all pests, and it leaves the soil quickly with no trace of harmful residue. The benefits in better growth are often noticed to last for several succeeding crops.

The early use of steam in combating root knot has been reviewed by Stone and Smith (1898). They may be looked upon as the fathers of practical steam sterilization of greenhouse soils in America. Since then a number of different methods have been

developed. Small quantities of soil have been steamed in a shallow bin with perforated pipes laid in the bottom ever since it was first described by May (1898). Steam chests of wood, concrete, brick or cast iron have all been constructed, even canners' pressure cookers have been employed. Popular models in England have been described by Falconer (1928), Hinks (1932), Lawrence and Newell (1938) and Bewley (1929), and in the United States by Newhall (1930), Fosler (1950), Ball (1950, 1952) and Steven (1953).

With all of these steam bins, the soil has to be brought to the steaming device and carted back again after it is heated, which involves time and much labor, although of late the use of power-driven, tractor-mounted, soil-moving equipment has greatly reduced both. Growers early devised ways of bringing steam to the soil, especially to ground beds to be treated for nematode control. This step, first announced by Selby (1906), doubtless was taken by many growers independently, perhaps before that time.

INVERTED PAN OR TRAY. For seedbeds and soil in shallow benches or even ground beds, a metal pan inverted and weighted down, under which steam is admitted for a period of 20 to 50 minutes, has served well at low cost for materials. Probably this was first used by the Wutrick Brothers in about 1895, and definitely was used by Bolley (1913) in 1911, who pictured it beside a portable steam boiler in North Dakota grain fields. It was formally described by Beinhart (1918), Selby and Humbert (1915), and more recently by Sackett (1927), Magee (1931) and Bewley et al. (1947). A variety of labor-saving devices to aid in the moving of the larger sized ones have been invented (Newhall, 1930; Newhall, Chupp and Guterman, 1942).

The latest substitute for a metal pan, described by Dimock and Post (1944) as a surface method of steaming benches, employs a rubberized cloth or stout kraft building paper or plastic tarpaulin, the edges of which are held down by weights while steam is directed between soil and cover. Where soil has been thoroughly loosened and steam pressure is below 15 lbs., such light weight covering is satisfactory and economical. The method demonstrates clearly that steam does not have to be driven into soil under great pressure but merely has to be exposed to the soil to effectively heat it. Deep penetration of heat below six inches does not take place

readily under the pan or surface method because the upper layers of soil become saturated, thus hindering further ingress. The method is better suited to bench than to ground beds.

Some ingenious ways of cutting down on the labor and equipment required to steam by the surface method have been described by Ball (1953*a*). They include the use of canvas hose laid on the soil surface in place of metal pipes as steam-conductor and a wooden frame covered with plastic tarp built over this hose, all of which together can be pulled by ropes to the next position every two or three hours without turning off the steam or walking on treated soil.

BURIED PERFORATED PIPE OR GRID. This method, first described by Selby (1906), was called the "ordinary greenhouse method" by Gilbert (1909), so general was its use in Ohio by then. It consisted of a series of pipes, usually one inch and perforated at one-foot intervals, laid in parallel trenches about a foot deep and 15 inches apart, through which steam was passed until the entire soil mass above was heated to 210°. There are many variations as to number, length and depth of pipes served by one steam header. It has been widely used in Europe and America. Its advantages lie in the thoroughness and depth of heating achieved. Bewley states that one year in four may be often enough to steam by this method in holding down root knot. Its disadvantage lies in the labor of burial and relocation every hour or so (Sackett, 1927; Newhall, 1930; Bewley, 1923, 1926, 1929, 1947, 1950). Smaller models have been placed in dump trucks or tip carts, and even wheelbarrows (Schwartz, 1933; Quantz, 1937; Roll-Hansen, 1949).

SPIKE, STEAM HARROW OR RAKE. This device consists of a grid of pipes with hollow pointed spikes at right angles to it, like a six-foot long hair-brush. The spikes, six or eight inches apart, are pushed into the ground, and the steam, led to it through a flexible hose, is turned on for 15 to 30 minutes at a time. Tests in Ohio by Newhall (1930) indicated it to be a cheap device for getting shallow or superficial jobs of heating done. The method has been discontinued in America. But Cunningham (1938) in Australia combined the features of a harrow with a pan and obtained pasteurization temperatures to a remarkable depth, 14 inches, in a minimum

of time, seven to ten minutes. It requires considerable labor and is slow.

BURIED TILE. Galloway, according to Stone and Smith (1898), was the first man to employ two-inch, porous, clay tile to conduct steam into a bin holding 72 cubic feet of soil to control soil pathogens. Stone and Smith (1898) showed how far apart the tile lines could be set. Their work laid the foundation for practical application of steam to greenhouse ground beds for the next half century. Their temporary system has given way to a permanent layout which is often put in before a greenhouse is built, at which time ditch-digging, tile-laying machinery can be used to advantage. Various layouts have been described (Brown, Baldwin and Connor, 1922; Brown, 1926; Newhall, 1930). The optimum depths and spacing of tile lines were found in Ohio to be 18 inches apart and 19 inches deep. Brown found lines three feet apart inadequate to control *Fusarium* wilt of tomato. One large grower in Ohio found lines two feet apart unsatisfactory and reset them all 18 inches. Lines 22 inches apart and only six inches deep sometimes failed to control tomato wilt at the Ohio Experiment Station. Steam has been successfully used in beds 40 feet wide, fed through only one header. Likewise lines as long as 110 feet have been steamed from one end with one or more boilers of 100 horsepower. Tile lines have been in annual use for as long as 27 years before being dug up and reset.

Areas of ground beds successfully steamed per boiler horsepower vary a good deal. With the shallower harrow and pan methods, up to three and one-half square feet were commonly treated, and the time to treat a unit area was less than an hour. With methods that steam soils more deeply, as buried pipe and tile, from six to eight square feet may be steamed per horsepower without waste, though much longer times per unit area treated are required. In several greenhouses 12 square feet per boiler horsepower have been steamed, and one or two have done 24 to 26 square feet, but such areas require from 10 to 24 hours of continuous steaming, and when a few tile are clogged, it may take many wasteful hours to find it out. From an economic standpoint, the best system is the one that forces the largest number of B.T.U.'s into the soil in the shortest time with the least labor. In Europe, where labor costs have been comparatively low, the tile method has not looked at-

tractive until recently on account of its high initial cost, but in America it has paid in the long run to put the money into such equipment lasting 20 to 30 years rather than into as many annual labor charges.

CONDITIONS CONDUCIVE TO EFFICIENT STEAMING. All workers agree that soil should be loose, free from lumps and preferably on the dry side in steaming operations. Steam flows through the paths of least resistance. As pointed out by Russell and Pethybridge (1912), water requires four times the number of B.T.U.'s that sand or clay does to raise it one degree F, since the specific heat of dry soil is only .23. So a soil with 60 per cent moisture requires two times the heat units that one of 20 per cent needs. They conclude that, if one could get 100 per cent efficiency, a pound of coal containing 12,000 calories should heat from 100 to 340 pounds of soil from 52° to 212° F. But in practice such an amount of coal heats only 30 to 100 pounds of soil; and to raise a ton of soil to 180° F requires about 50 pounds of coal, so one gets only about 30 per cent efficiency. If a pound of coal potentially should heat 100 pounds of soil from 52° to 212°, and if a six-inch acre weighs two million pounds or a thousand tons, it should take about 13 tons of coal to steam an acre one foot deep. Assuming 30 per cent efficiency, it would actually take over 40 tons of coal. This is roughly what many greenhouse tomato growers in northern Ohio used, according to Newhall (1930) and Senner (1934). Roll-Hansen (1949) gives the specific heat of soil at 0.5, which means that 500 kilo-calories are required per cubic meter per degree rise. Since one kilo of steam is good for 600 kilo-calories, it requires 75 kilo-grams of steam to heat one cubic meter of soil to 90° C. Under ordinary good conditions, he states that about 60 per cent efficiency is achieved today.

Bewley with tray or inverted pan used 3200 pounds of fuel to treat 2160 square feet to a depth of 12 inches, which is one and one-half pounds of coke per cubic foot of soil treated or 32.6 tons per acre. In another test he used two pounds of coal per square foot with both the buried tile and the inverted pan methods or 43 tons per acre, and he gives nine square feet and three square feet as the amounts one can expect to do per boiler horsepower, respectively. It seems that from two to four cubic feet of soil an hour per boiler horsepower, no matter what method is employed,

is what one should be able to steam, depending upon soil moisture, original temperature, size of conductor, distance from the boiler and firing efficiency.

A few items contributing to the maximum efficiency of the steaming method would be withholding moisture from the soil for a month prior to treatment, insulation of the pipes from boiler to site of steaming as advocated by Bewley, a water trap to collect condensate before it enters the soil, and a pressure gauge at the site of steaming rather than on the boiler, as advocated by Brown, Baldwin and Connor (1922). Brown (1926) points out that it is the volume of heat units passing into the soil that counts and not just the boiler pressure, which makes size of pipes of great importance. Ball (1952) stresses adequate sized conductor pipes, particularly where low pressure steam is employed. Newhall, Chupp and Guterman (1940) give tables to show the amount of steam carried by pipes of various sizes under various pressures, together with the line drop or loss with distance from the boiler.

No one stresses the need for high pressure steam any more; in fact, many hot water-heating plants have been converted by florists to low pressure steam generators in the last ten years for soil-steaming purposes, with almost universal satisfaction (Ives and Ives, 1953). The pressures are from five to 15 pounds per square inch. The Thomas surface method of steaming works well on low pressures. Almost no pressure was employed in the Moore copper kettle method, described by Bewley (1923), or in the electric pan steamer, described by Newhall (1940). Scheffer (1930) employed but six to eight pounds pressure with apparent success. Senner (1934) concluded that a final soil temperature of 212° F is all that can be obtained, regardless of initial steam temperature or boiler pressure. High boiler pressures did not materially lower the total steam required nor did they greatly affect the amount of water which normally accumulated in steamed soil. He believed the so-called merits of high pressures were largely mythical. Jacks (1953) found high and low pressures to give equal results. However, Bewley (1926) and Hunt et al. (1925) both found with the inverted pan that doubling the steam pressure almost doubled the rate of heat penetration into the soil. Perhaps the same could have been obtained by an increase in the size of the steam conductor pipes.

Addition of formaldehyde to the soil to be steamed or its introduction into the steam line during the process has been tried by Winston (1913), by Beachley (1937) and by Manns (1947). It is said to reduce the time required to steam a unit area and to increase the efficiency of low temperature heating, but Hunt et al. (1925) got no appreciable benefits from the addition of formaldehyde. The method is not widely used because formaldehyde has such a high affinity for water that it will not go any further into the soil than the steam condensate that carries it, because of the time required to rid the soil of the vapor, and also the discomfort to the operators.

By clubbing together, growers can spread the high cost of equipment, as was done in Germany by Erven (1938) and as has since been done in the Buffalo, New York, area, where 12 men in 1950 bought a 25-horsepower flash boiler on wheels capable of treating 600 cubic feet of soil in five hours. Each grower pays a few cents a square foot, which amortizes the $3000 investment in six years and pays for fuel and a man to operate the machine. In England and Europe for many years a grower has been able to rent a 20-horsepower locomotive type boiler for soil-steaming purposes at certain times of the year. Very recently in the United States a low-priced, ten-horsepower, oil-burning boiler on two wheels has been gaining favor of many florists for steaming benches and potting soil (Ball, 1953).

Taking advantage of the slowness of cooling of hot soil, investigators have recommended shutting off the source of heat, be it steam or electricity, and utilizing the fireless cooker principle to finish off a batch of soil when once it is brought up to 160° or 180° F (Horsfall, 1935; Lawrence and Newell, 1938). Pasteurizing temperatures developing in compost piles is a gratuitous form of heat that often kills pathogens.

DANGERS OF REINOCULATION. Edgerton (1915) first pointed out that *Pythium* grows much faster in steamed than in unsteamed soil. Bewley (1923) found that *Verticillium* travels through freshly steamed soil three times as far in six weeks as in untreated soil. Hartley and Pierce (1917) decided that steaming outdoor forestry seedbeds is not recommendable because of the extent of loss from reinoculation with seedling pathogens. Walker and Smith (1930) and others have made use of this phenomenon by

regularly steaming soil previous to its inoculation with *Fusarium conglutinans* in testing cabbage seedlings for susceptibility in their program of breeding for resistance. Dimock (1941) found *Rhizoctonia* to grow as fast through unsteamed as steamed soil when host plants were close together. Hartley (1921) pointed out that the presence of saprophytic fungi, particularly *Rhizopus nigricans,* could be counted on to lower the parasitism of *Pythium debaryanum* when the latter was reinoculated into steamed soil.

If sources of atomic heat ever become cheap enough, steam could be employed more extensively outside of greenhouses. The techniques are known for applying it, but the cost of fuel limits its use to land producing high value crops.

HOT WATER

Byars and Gilbert (1920) eradicated *Heterodera, Rhizoctonia* and *Pythium* from soil in five-inch pots by five-minute immersion in water at 98° C, from eight-inch pots by pouring two to three liters of boiling water over each, and from shallow benches by application of seven gallons per cubic foot. Fleming (1925) showed that all stages of the Japanese beetle were killed in water at 112° F, a temperature not too injurious to plant roots. Compton (1936) devised a portable hot water sterilizer to be used at the end of a steam line for killing nematodes in soil. This is pictured by Ball (1939) and by Newhall, Chupp and Guterman (1940). Newhall (1930) compared steaming by the buried pipe method with a hot water drench in a ground bed of a sandy soil near Cleveland, Ohio, and found more than twice as many nematode galls on 1000 tomato plants from the hot water-treated as from the steamed soil. Its relative inefficiency (one pound of boiling water containing only one-sixth as many B.T.U.'s as a pound of steam at the same temperature), coupled with the more puddled condition of soil treated with hot water make its use unpopular. Bewley (1923) found that it took two million gallons of water per acre or four and one-half gallons per square foot by a surface drench method; and by mixing four to ten tons of caustic lime in the soil first and leading the hot water into parallel trenches, a deeper job could be done with 180,000 gallons of hot water per acre. But in a four-year test of the comparative values of steam and hot water on the yields of tomato, steaming was

found to be far superior. Modern methods of steaming soils are reviewed by Bronsart (1931) for Germany, by Bewley (1941) for England, for Norway by Roll-Hansen (1949).

ELECTRIC STERILIZERS

Stone and Smith (1898) tried to electrocute the root knot nematode in greenhouse soil and concluded that it could be done only by raising the entire mass of the soil to the thermal death point of the nematode, which is about 120° F.

Elveden (1921) compared electric with a number of other ingenious methods of treating soil but left no detailed account of his electrical equipment. The depression of the early 1930's induced electric power companies in America and Europe to encourage research on many agricultural uses of electricity, including soil pasteurization. Out of this, two general methods of electric pasteurization emerged. In the first, direct heating or soil resistance method, the current is passed through the soil between two or more electrodes. The soil becomes heated by reason of the resistance it offers to the passage of the current. In the second, the indirect heating method, covered resistance type heating units are buried in the soil and impart their heat to it by thermal conductance as the current is passed through them at a constant rate. Early work on the resistance method was done about 1931 in Holland by Kroft and Groen (1933) of a Holland power company, and in the United States by C. W. Wildebour of the Puget Sound Power and Light Company in cooperation with C. F. Doucette of the U. S. Department of Agriculture, Etomology Laboratory, at Sumner, Washington, according to Scott (1932). The American workers were able to raise 20 square feet of bench soil from 60° to 180° F in two hours with an expenditure of 70 kilowatt hours on 230-volt alternating current. This was repeated by Fee (1933), and by Krewatch and Kable (1933) who pointed out in a comprehensive report a number of difficulties and limitations involved in employing this method, such as the need for an extra heavy service line, the need for soil moisture, and proper compaction of the soil against the electrodes. In Germany, Dix and Rauterberg (1933) used a three-phase circuit and a transformer with variable capacity between 3.6 and 60 amperes at voltages between 2750 and 200. They varied the distance be-

tween their vertical parallel electrodes from eight to 78 inches. By using strong currents for relatively short periods of time, greater economy was obtained, and a cubic yard of soil was heated to 70° or 80° C with the expenditure of but nine to 16 kilowatt hours, or less than one-half kilowatt hour per cubic foot. The necessity of having a transformer and the hazards to the operator discouraged further work with exposed vertical electrodes.

Scott (1932) built the first cabinet type electric pasteurizer with vertical plates, many of which are still in use, but Blauser (1934, 1935) made an improvement by substituting two horizontal electrodes, on the top and bottom of the box, for the numerous vertical electrodes used by Scott. Blauser, and Tavernetti (1935) both pointed out that resistance to the current is directly proportional to the distance apart of these electrodes and at the same time is inversely proportional to their area. These facts, together with the limitations on maximum current available to most users, determines the proper size and depth of a cabinet of this type. Similar experiments were conducted in Holland with horizontal electrodes in a cabinet type pasteurizer by Kröft and Groen, and by Muyzenberg and Rijn (1937) who studied the effects of electrolytes, moisture and compression on conductivity of sandy soils. Their figures on current consumption were rather high, being 1.6 to four kilowatt hours per cubic foot, but their end temperatures were also high, being 99° C. They confirmed Blauser's conclusions that sand must be watered with a dilute electrolyte, such as potassium chloride or potassium nitrate, to insure rapid satisfactory conductance.

To eliminate the hazards inevitable where one is handling 230-volt, 30- to 60-ampere lines, Carney (1932) built a cabinet type pasteurizer with covered heating elements having a fixed current demand. This was tested by Horsfall (1935), and by Newhall and Nixon (1935) who made many comparisons between this and the direct heating type, concluding that the indirect type is better adapted to general use because of its greater safety and its known fixed demand on the current supply.

Ordinary soil-heating cable was found unable to withstand the temperatures required for soil pasteurization. The induction principle, so successfully employed in certain types of heating, was also found to be impractical because of the expense of equipment and the high current demand.

A continuous or semi-flash type electric soil pasteurizer, in which small piles of soil are dragged across an electrically heated steel plate at a rate which assures their reaching a temperature of 180° F by the time they fall into waiting flats at the end, was described by Newhall (1940), and another by Caple (1940), as rather successful. A similar continuous pasteurizer, described by Tavernetti (1942), heated one cubic foot of soil per thousand watts of heating capacity. He pointed out (1950) that if a cubic foot of dry soil requires 1800 B.T.U.'s to heat it from 50° to 200° F, it will require 1350 more B.T.U.'s if it contains 15 per cent moisture.

Experiments involving the generation of steam by electric heaters, either in a closed cabinet filled with flats of soil or under an inverted pan over soil in a ground bed, are of some interest because in neither case was the steam under any pressure, and yet rather good penetration of the soil was achieved to depths of ten inches at an expenditure of 1.76 kilowatt hours of current. This, in general, compares favorably with the cost of steaming with coal as fuel in small operations, although it is slower. With current costs of two cents per kilowatt, electric steaming of soil is economical of everything but the operator's time.

A number of attempts have been made to use very high frequency current, very high voltages between plow points, and other devices, but none of them has proved effective or practical. In some cases the designers have been more interested in making something that had sales appeal than they have in testing and establishing the validity of the principle involved.

The one factor limiting the use of electricity in soil sterilization is not the cost of the current but the size of the service line required to get an appreciable amount of pasteurizing done in a reasonable amount of time. It is like steaming an acre of soil with only a quarter-inch steam line. If one could operate on the offpeak load at the low rates for electricity after midnight and have the operation all automatic, so no hand labor was employed, it would be an economical way of pasteurizing piles of compost soil.

FLOODING

Plant pathogenic organisms require oxygen for respiration, hence are rather easily drowned. Some, however, like the water molds, thrive in the presence of water, and some nematodes and

higher fungi produce resting stages and sclerotia that can withstand a considerable period of submersion. Addition of numerous fungicides, insecticides or nematicides to the water is designed to hasten or otherwise improve the lethal action. Most of these substances go no farther into the soil than the water they are dissolved in. Some substances may be so promptly altered by the action of organic chemicals and soil organisms as to be rendered ineffectual in a few days or even hours under warm moist conditions.

According to Martin (1940), flooding was practiced by European grape growers with some success in their fight against the Phylloxera in the last century, and against wireworms recently in California by Campbell and Stone (1938). The work of Brown (1933) is of interest because he concluded that flooding for a long enough period to eliminate eggs of the root knot nematode from the organic soils of the delta region of the Sacramento and San Joaquin Valley in California would take the land out of production for nearly two years, which was not feasible. Michelbacher, Bacon and Underhill (1953), however, found that a seven- to ten-day period of flooding in the same region was adequate in the summer to eliminate the garden centipede which could be killed in as few as 48 hours at a temperature of 100° F. Moore (1949) was successful at eliminating *Sclerotinia sclerotiorum,* the cause of a severe stem rot of beans and other vegetables in certain Florida soils that have a compact subsoil. He found that these sclerotia would rot in 23 to 45 days in either muck soil or marl, regardless of whether flooding was continuous or at three-day intervals. Addition of green organic matter to the surface had no important effect on the process. Pink rot of celery was also controlled in Florida by Brooks (1942). The effects of flooding and of drying soils for the control of root knot nematode are well summarized by Kincaid (1946).

One of the largest most interesting flood-following projects in the world is that of the United Fruit Co. in Honduras for the eradication of *Fusarium oxysporum* f. *cubensis,* the fungus causing Panama disease, or banana wilt. If land, after flooding three to six months, remains relatively free of the disease for six years, it will pay to flood and replant thousands of abandoned acres in countries politically stable enough to warrant spending the millions of dollars required for such large-scale operations. Two of the conditions that must be remedied, according to Stover, Thornton

and Dunlap (1952, 1953), are that the rivers used to replenish the water, lost by evaporation and percolation, may contain as many as 150 spores per mililiter and that flooded soils are more favorable to growth of *Fusarium* after drainage than non-flooded (Stover, 1953). No soluble fungicide has yet been found to show much promise under the conditions of rapid decomposition obtaining in these tropical waters.

Oostenbrink and Besemer (1950) found that the cysts of the golden nematode (*Heterodera rostochiensis*) could withstand 15 months in water, so that flooding seems hopeless as a control for this pest. There is always the danger of spreading some unsuspected pathogen in a flooding program, which makes it somewhat hazardous. For example, Perry (1953) points out that the awl nematode (*Dolichodorus heterocephalus*), the cause of heavy losses in Florida, evidently prefers damp soils in wet locations. Hence flooding might actually increase its spread.

SOIL FUMIGATION

CARBON DISULFIDE

This fumigant is of considerable importance, not perhaps for its current usefulness so much as for its historical interest. Up to 1945 it was the most widely used of all soil fumigants, particularly against Scarabaeid larvae (Gough, 1945). It is surprising how many of the methods, rules and techniques so hopefully worked out the past 20 years for other soil fumigants were well developed or discarded half a century ago when the grape-growing industry of France and Germany was fighting Phylloxera for its life. As early as 1877 Dr. Crolas formulated ten rules for the use of carbon disulfide in soil fumigation, which rules have remained sound for 60 years. Good early histories of carbon disulfide soil fumigation are given by Bourcart (1913), Vermorel and Crolas (1915), Vogt (1924), Fleming and Baker (1935) and Gough (1945). From these we learn that by 1884 a million acres of soil were treated; in 1890 some 250 tons of "vaselinated sulfides", containing 30 to 70% CS_2, were used in French vineyards, and in 1895 approximately 150,000 acres of vineyards were fumigated. The practice was then believed to be taking its place in agriculture like that of fertilizers. But four years later it was being discarded after the introduction of Phylloxera-resistant root stocks from America.

Although usually injected into holes 20 inches apart, the method

of spraying carbon disulfide in the furrow while plowing was enthusiastically adopted by many larger vineyardists until it was painfully learned that this method was inadequate. A less phytotoxic method of application, proposed in 1875 and developed rather extensively, employed irrigation water piped to the fields, sometimes several miles, containing a 0.5 per cent solution in the summer and a 0.7 per cent solution in the winter. A dosage of 2600 gallons per acre contained approximately 88 pounds of carbon disulfide.

It was learned that any gas dissolved in water does not penetrate soil any further than the water itself. Accordingly impregnated cubes of wood, heavy oils and even gelatin capsules were tried in place of water, but none was better than carbon disulfide alone, and no other chemical of the many tried was its equal. Many workers came to believe it had fungicidal properties against *Dematophthora necatrix, Fusarium dianthi* and *Rhizoctonia* species, as well as being lethal to the root knot nematode. By 1905, 99,000 lbs. were used in the province of Palatinate, Germany, where no specific parasites were known, according to Loew (1909).

It was recommended against beet root knot at 1580 pounds per acre, and wetting the soil after the injections were made was common practice. The many types of equipment employed, all illustrated by Vermorel and Crolas (1915), remind us of modern machines.

Over the 60-year period when carbon disulfide was much used, a great deal was learned of a rather fundamental nature about its effects on pests and on their hosts, about equipment for applying soil fumigants, and about the proper soil conditions for fumigation in general (Fleming, 1923, 1925). Its use increased crop growth as well as development of nitrifying bacteria and nitrates, while it reduced water retention in soils, inhibited denitrification, and suppressed most bacteria and protozoa. It thus greatly changed a soil's biological equilibrium and perhaps helped plants obtain more potash and phosphorus. As pointed out by Fleming (1925) and Fleming and Baker (1935), carbon disulfide has been used with success against ants, raspberry borer, white grubs, June beetle larvae, Oriental beetle, mealy bug, symphillids and cock chafer, while it has not been so successful in eradicating wireworms, cabbage maggot, peach borers, root aphids and sugar cane beetles because soil conditions and resistance make its action so

variable. Some plants, such as cyclamen, are injured instead of being stimulated. Soil temperature and moisture were found important in determining the efficacy of a given dosage against Japanese beetle larvae. Elevation of the temperature above 50° increased and elevation of soil moisture decreased the kill. A second treatment of a given soil persists five times as long as the first, the soil removing in some way much of the first charge, some of the second, but almost none of the third (Bywater and Pollard, 1937).

The movement of carbon disulfide vapor through soils was shown by Hagan (1941) and Hanneson et al. (1945) to be chiefly dependent upon the degree of porosity of the soil, which in turn is largely influenced by compaction and water content. A wet plow soil is impervious to the gas. Differences in partial pressures of the gas in different places, soil temperatures and degree of adsorption play minor roles. Soil permeability decreases to almost zero as soil moisture rises and approaches the moisture equivalent.

Use of carbon disulfide in emulsified form was popular at one time. While its efficiency is said to be cut in half by emulsification, its safety to plants is so much increased and the accuracy with which it may be applied so enhanced that it has been recommended in the United States in this form probably more often than by injection. This development was greatly spurred on by the appearance and rapid spread in New Jersey of the Japanese beetle and by the necessity of finding a safe and not too costly way of controlling it in nursery stock shipped out from that region and in lawns and golf courses. Johnson (1927) treated a total of 100 acres on 366 properties in Connecticut with an emulsion, using fire hydrants and a "Thomas proportioning machine" with a capacity of 600, and in one case 1200, gallons an hour. Fleming and Baker, and Merritt et al. (1933) treated similar large areas of lawn, the latter using two and one-half-inch porous hose rather than nozzles. While most insects succumbed to moderate dosages, the larvae of the Coleoptera (wireworms) required five to ten times more. Lathrop (1942) found that carbon disulfide emulsion actually increased the number of blueberry thrips. Schwardt and Lincoln (1940) found it the best of six fumigants in the control of the alfalfa snout beetle, but it took 1800 pounds per acre to kill 98 per cent of them. The buried tile lines in the ground beds of a greenhouse were used by Riley (1928) to introduce this fumigant

into the soil in the successful destruction of the garden centipede. Lines were 22 inches apart and 175 feet long, and by passing steam through the carbon disulfide container, 15 pounds of the gas were volatilized in a few minutes and driven into each line of tile one at a time. Thus an area of nearly 200 square feet was fumigated with 90 pounds or 1900 pounds per acre.

Some success attended the use of CS_2 emulsion in California against *Armillaria* root rot of citrus trees (Fawcett, 1936; Thomas and Lawyer, 1939) and against *Omphalia* root rot of date palms (Bliss, 1944*a*, *b*, 1947, 1948), it being judged the most satisfactory of three fumigants tried in the field. It penetrated much deeper than chloropicrin and was easier to measure than ethylene oxide. At rates of 1000 to 3000 pounds per acre, carbon disulfide will control nearly all of the root knot nematode in a greenhouse, but, according to Young (1939, 1940), these amounts are not able to kill all of the weed seeds or to control *Fusarium lycopersicum* on tomatoes, and it is hazardous to use. Accordingly, this material never became very popular with greenhouse vegetable growers who were fighting root knot nematode. The hazards were partly overcome, but not its poor fungicidal properties, by using emulsions (Schaffnit and Weber, 1929; Chapman and Parker, 1929; Gleisberg, 1930). Guba (1932) endeavored to correct this situation by combining carbon disulfide emulsion with formaldehyde, but the expense and labor involved deterred its general adoption. The fact that carbon disulfide is dangerously inflammable and explosive, especially if mixed with three times its volume of oxygen or an equivalent amount of air, having an ignition point of only 300° F and still lower on the surface of glass, copper, steel or chromium, makes its use rather hazardous. On the other hand, its volatility is in its favor. It has a vapor pressure of nearly 300 millimeters at 20° C, which means that 1000 cubic feet of air can hold up to 77 pounds of the vapor. Its fungicidal properties probably derive from its slight solubility in water, while its fumigating power against insects and nematodes may derive from its great solubility in fats, waxes and oils. All good soil fumigants seem to have this latter property in common. The actual lethal mechanism involved, once the chemical diffuses into a fungus or is taken into an insect by respiration, is largely a matter of conjecture, but there are probably several ways that death is brought about.

CHLOROPICRIN OR TEAR GAS

After World War I, large stocks of chloropicrin were on hand in several countries, the United States alone having reached a manufacturing capacity of three million pounds a month by 1919. The results of many investigators soon established its high unit toxicity to all sorts of living organisms, including insects, fungi, nematodes, bacteria and weed seeds. Some of this work may have been stimulated by the interesting observation than English factory workers, who filled artillery shells with chloropicrin, were singularly free from influenza, only two to four per cent of them contracting the disease as compared with 25 to 68 per cent among other workers (Shufflebothom, 1919). Among the 533 references to chloropicrin listed by Roark (1934) are 24 papers dealing with the toxic properties of this gas to microorganisms. Besides the bibliographies of Gersdorff (1930), Jackson (1934) and Roark and Bushey (1935), more than one hundred other papers dealing with this gas as a fumigant have been reprinted, whole or in part, since 1938 in the Larvacide Log published by Innis Speiden Company, now Larvacide Products Co.

Moore (1918) showed chloropicrin to be 283 times as toxic to certain insects, in air, as carbon disulfide. It promptly became a leading space fumigant for warehouses and flour mills, a place only recently disputed by methyl bromide (Johnson, 1937) and ethylene dibromide (Anon., 1946). Its extended use as a soil fumigant was brought on largely by a crisis in the Hawaiian pineapple industry (Nelson, 1951). Johnson (1935) found chloropicrin and carbon disulfide the best of 40 chemicals tested between 1927 and 1932 against the root knot nematode and other pineapple root troubles. Others were quick to show that chloropicrin was very effective in restoring yields of pineapples and of vegetables grown on "worn out" soils, and to emphasize its biotic rather than chemical role (Johnson and Godfrey, 1932; Cooke, 1933; Godfrey, 1934*a*, *b*, 1935, 1936; Howard, 1938; Stark, Smith and Howard, 1939; Stark, Howard and Smith, 1940; Smith and Howard, 1942).

Chloropicrin has been marketed chiefly in cylinders of various sizes, in one-pound dispenser bottles and as an aersol under pressure.

CONFINEMENT INCREASES EFFECTIVENESS AND ECONOMY. The high cost of chloropicrin together with its high vapor pressure and

hence rapid escape from the soil make some sort of seal imperative if dosage rates are to held to economic levels. Godfrey (1934) and Godfrey et al. (1934) found that the following made good coatings for paper to confine chloropicrin: cellulose acetate, 10 to 15 per cent solutions of animal glue, water glass, and various hydrophyllic colloids like starch paste, gelatin, and several other glues. Poor results were secured with varnish, paint, lacquer, enamel, rubber paint, graphite roofing paints, and shellac. Casein glue was about the only thing at that time found highly efficient by the United States Forest Products Laboratory in holding back carbon disulfide.

For several years glue-coated paper was used on seed beds, cold frames, bench soil, etc. when fumigated with chloropicrin. Merely sprinkling the surface of treated soil with from one to two pints of water per square foot within 15 minutes of fumigating has given fairly satisfactory retention of the gas, perhaps 85 per cent (Godfrey and Young, 1943; Stark, 1948; Lear, 1951). With the coming of plastics the picture changed, especially with the wider use of methyl bromide fumigants. First came the plastic-coated fabrics, as " Stericloth " and " Fiberthin ", then the straight plastic tarpaulins, exemplified by " Visqueen ", " Velan " and other cellulose and vinyl acetates. For weed seed control in seed beds, greenhouse benches or ground beds, the material is commonly injected in holes nine to 12 inches apart, four to six inches deep, at two to four milliliters per injection (Cooke, 1933; Garner, 1940; Godfrey, 1939; Godfrey and Young, 1943; Shippy, 1941; Clayton et al., 1949; Leukel, 1942; Jacks, 1953). Larger areas in or outside of greenhouses are treated with power-driven, multiple-row, sub-surface, continuous-flow injectors which have reached their highest state of development in Hawaii (Nelson, 1951). Closed gas-tight fumigation chambers for potting soil and mushroom-casing soil are sometimes used where fungi and insects are a problem and steam is not available (Thomas, 1942; Kligman, 1942).

The latest method of dispensing chloropicrin is from a cylinder as an aersol propelled by methyl chloride in the fumigation of potting soil, composts and seed beds under gas proof tarpaulins (Newhall, 1953).

The properties of chloropicrin which make it a good herbicide

render it extremely phytotoxic to living plants which must be removed from greenhouses prior to soil treatment. Moreover, the gas must escape completely from treated soil before the latter can be used. This may take from five to 20 days, depending on several factors—temperature, rainfall, tillage.

The killing range of chloropicrin for nematodes has been found by several workers to be about six inches from point of injection in ordinary soils, and to vary surprisingly little with increased dosages (Newton et al., 1937; Chitwood, 1939; Taylor, 1939; Stark, 1948). To kill the resting sclerotia of several important pathogens, e.g., *Rhizoctonia, Botrytis* and *Sclerotinia,* requires about twice the dosage needed for their vegetative stages. Even then the moisture content is important.

In his study of the dispersion of fumigants through a lateritic soil in Hawaii, Schmidt (1947) found that chloropicrin moved more rapidly through soil with 20 to 25 per cent moisture than through one with 10 to 12 per cent, as measured by kill of rice weevil. The reason assigned was that in a soil with so much colloidal matter, agglomeration of soil particles occurs at the higher moisture content which opens up larger pores. Smith (1938) found a soil temperature of about 20° C and soil moisture of ten to 15 per cent optimum for the death of soil bacteria and fungi. Of 600 soil fungicides tested by Schmitt (1949), only nine were very effective, and of these chloropicrin was lethal to the mycelium of five common pathogens in soil at one-eighth the dosage of its nearest competitor, allyl bromide. There seems to be general agreement that chloropicrin is more fungicidal and herbicidal than any of the other common soil fumigants (Shippy, 1941; Godfrey and Young, 1943; Tam, 1945; Newhall, 1946; Stark and Lear, 1947; Jacks, 1945, 1948*b, c;* Lindgren and Henry, 1949; Jacks and Smith, 1952; Jacks, 1952). Out of 30 kinds of seeds tested by Welton and Carroll (1941), only those of lamb's-quarters, orache and white clover were resistant to a dose of 25 to 30 ounces of chloropicrin per cubic yard. Morrison and Mote (1941) found chloropicrin toxic to symphylids in soil but concluded that it requires a rate of 300 pounds per acre at a cost of $200 to $300 to control them. He found chloropicrin dispersed to greater distances than D-D, but Stark and Lear (1947) found D-D to penetrate much deeper than chloropicrin in a closed container.

Stark (1948) reported adsorption to play a very important role in the practical application of chloropicrin because, whereas the dry sand fraction of a certain mineral soil could absorb but 0.18 per cent of its weight of chloropicrin, the silt fraction but 0.8 per cent and the clay fraction only 3.2 per cent, the colloidal clay fraction might adsorb nearly ten per cent of its dry weight at 30° C. So it takes up to 50 per cent more chloropicrin to achieve good results in some clay soils. The process was exothermic, reversible, unimolecular and almost linear in relation to temperature, though at lower temperatures more adsorption might take place as a result of capillary condensation.

Crops growing in closely planted rows, such as carrots, sugar beets and tobacco, need over-all soil treatments, but Taylor (1941), Taylor and McBeth (1941) and Walter and Kelsheimer (1949) have shown how costs of treatment for tree sites, vine crops and hill crops, such as watermelons, can be reduced by 50 to 80 per cent by spot injections. In such cases a water seal becomes more feasible and greatly adds to the efficiency. Since even an over-all treatment for nematodes never eradicates completely and has to be repeated, it is clear that the economy of spot treatments in the course of time can be very great. For crops like pineapples and tomatoes, even an in-the-row treatment can bring about considerable economy over an over-all treatment. However, inferior increases in yields of fall grown cucumbers were reported from row treatments with D-D by Epps (1950).

The effect of fumigation with chloropicrin on the soil flora, on biologic activity and on chemical constituents has been rather thoroughly studied by Johnson (1935), Cooke (1933), Smith (1938), Matthews (1924), Stark, Howard and Smith (1939), Schchepetik'nikova (1942), Schchepetik'nikova and Scheremisova (1937), Stark and Smith (1938), and Tam and Clark (1943). The earlier work showed that, as in steaming, there may be temporary inhibition of nitrification after treatment, an increase in ammonia and a very large increase in root growth, since total nitrogen is sometimes raised. Plants were found to pick up one and one-half to three times as much nitrogen and one and one-half times more P_2O_5, from which Russian workers argue that chloropicrin helps to mobilize more nutrients by intensifying microbial activity and organic decomposition. A large portion

of the soil's nutrients must be locked up in the bodies of microorganisms, much of which is liberated on their death.

Use of emulsions to hasten penetration and give direction to applications has been tried (Jacks, 1951). Todd, Lucas and Moore (1950) obtained control of tobacco black shank, but not of weeds, with 38 milliliters per gallon per square yard of tobacco seed bed. The fact that it may take three to four times as much per acre has mitigated against wide acceptance of this method of application (Taylor, 1941).

Sugar beet-receiving stations in some places have had a problem of disposing of their screenings when they contained sclerotia of the fungus *Sclerotium rolfsii.* Davey and Leach (1941) found chloropicrin effective at disinfesting the piles but not recommendable because of the difficulty of confining the gas, a problem that would seem to have been met, now that plastic tarpaulins of almost any length and width are available, and since chloropicrin may be obtained in pressurized containers.

RESPONSES OF FIELD CROPS TO CHLOROPICRIN. Although not recommended for field crops on account of the expense, McLaughlin and Melhus (1943) pointed out that fall applications of chloropicrin at three milliliters per injection on ten-inch centers caused better germination and growth of spring-sown oats, barley, wheat, rye, flax, cowpea, alfalfa and sugar beet. Barley yields were increased 450 per cent and sugar beets 606 per cent. Isolations showed that there was less *Pythium* and other seedling-rot genera in treated plots. On the other hand, with spring treatments Bruehl (1952) obtained reductions in yields only of wheat and barley.

VIRUSES DESTROYED. Several fumigants, including chloropicrin, were found by Johnson (1945) to control wheat mosaic, presumably by destroying some unknown vector. Allen (1948) found chloropicrin and other fumigants, such as D-D, but not ethylene dibromide, capable of destroying the soil virus causing big vein of lettuce. Rich (1950) noted that chloropicrin in xylol, 1 : 4, would do the same at 500 lbs. per acre, but not chloropicrin alone.

ECONOMICS. Efforts to reduce the cost of fumigation with chloropicrin have included adding cheaper diluents with nemacidal

powers of their own, such as ethylene dichloride (Chitwood, 1941; Newhall and Stark, 1942), and adding D-D mixture. The possibility of getting synergistic effects has not been explored very thoroughly, since much cheaper replacements for chloropicrin have been appearing, e.g., methyl bromide, D-D mixture and ethylene dibromide.

There have been several cases where soil fumigation with chloropicrin was disappointing, too costly or devastating, due to recontamination with certain pathogens, the latter being particularly true with cereal crops (Bruehl, 1952). Pea root rots were not well controlled (Reinking and Newhall, 1950), nor sclerotia in surface piles of beet screenings (Davey and Leach, 1941), nor the potato wart (*Synchytrium*) (Gimingham and Spinks, 1919). Expense rules it out against beet nematode and wireworm (Karab and Butovski, 1940; Kapshuk, 1933; Decoux and Roland, 1938; Stone and Campbell, 1933; Morrison and Mote, 1941). Since it acts as an irritant against insects, symphylids are driven to migrate further down in the soil and thus to escape. The fact that chloropicrin is 40% more soluble in cold water (0° C) than in warm (25° C) helps explain subsequent damage to plants if soil is treated when cold and later warms up after being planted (Shepard, 1951).

Because of its ability to destroy a great variety of soil pests, chloropicrin still is widely employed where the value of the crop is high and its use therefore justifiable. Its cost, inevitably high by reason of its nitrogen content and the expense of its manufacture, together with its lachrymatory, phytocidal and corrosive properties, have led to the discovery of safer, cheaper soil fumigants. But for 20 years it has been a yardstick by which the newer materials have been measured.

DICHLOROPROPENE-PROPANE MIXTURE

With the discovery of the nematocidal properties of D-D mixture by Carter (1943, 1945) in Hawaii, the practice of soil fumigation was greatly stimulated (Anon., 1946). This by-product in the manufacture of allyl alcohol, as one step in the petroleum plastic industry, is a 2:1 mixture of a 1,3-dichloropropene and 1,2-dichloropropane with minor amounts of lighter and heavier saturated and unsaturated hydro-carbons. The fraction toxic to nematodes, wireworms and fungi is the 1,3-dichloropropene (Lange, 1946;

Newhall and Lear, 1948; Zentmyer and Klotz, 1949; Lear, 1951). Boiling points, however, are close, and separation of the fractions is not practicable or necessary; there may even be some beneficial action from the other components (Carter, 1945). It has a boiling range of 95° to 150° C, and its volatility consequently is low enough to make sealing it in the soil unnecessary, thus giving it a great advantage over chloropicrin in addition to its lower cost. It is somewhat less disagreeable than chloropicrin to handle, but it can burn the skin and cause some discomfort from inhaling.

In general, D-D lacks fungicidal properties, according to Parris (1945) and Newhall and Lear (1948), but Clayton et al. (1949) found that it controlled *Sclerotium rolfsii* in one field on tobacco, though not *Rhizoctonia*. Stark and Lear (1947) obtained some control of *Fusarium* pea seedling rot with it in greenhouse tests, while Zentmyer and Klotz (1949) found that both D-D and Dowfume-N killed *Phytophthora cinnamomi* and *Phytophthora citrophthora* at dosage rates that did not eradicate the normal soil flora. Jacks (1945) got some damping-off control with it. From extensive work on lima bean root rot control in California, Middleton, Stone and Kendrick (1949) conclude that D-D has some fungicidal properties, as it was the only thing that controlled both wireworms and the fungi implicated in the root rot complex, being more effective than ethylene dibromide, although the latter is better against wireworms. Some success was likewise obtained against *Sclerotium rolfsii* attacking sweet potatoes by both D-D and ethylene dibromide in Louisiana, according to Martin (1953).

The nematocidal and insecticidal properties of D-D mixture are excellent in field use at dosage rates of from 200 to 600 pounds per acre; its cost is from $35 to $90. Its effectiveness and low cost against root knot nematode of tomato in greenhouses were demonstrated in comparison with other fumigants by Stark, Lear and Newhall (1944). Its use has greatly increased sugar beet yields where beet nematode (*Heterodera schachtii*) is serious (Anon., 1947; Thorne, 1952). Benefits from root knot control on tobacco are reported in Florida by Kincaid (1948), in North Carolina by Garris (1953), and on cucumbers by Epps (1950) in South Carolina. The meadow nematode was controlled on tobacco in Canada by Koch and Stover (1950) and by Clayton and Ellis (1947) who got good root knot control with 200 to 400 pounds

applied seven to ten months before sowing vegetable crops. July and October treatments were better than March treatments. Warren (1950) found D-D better than ethylene dibromide against root knot on sweet potatoes and melons in Indiana. Mullin (1953) controlled cracking of sweet potatoes, which was regarded as caused by some nematode not specified. In California, Stone (1944) showed it to be superior to carbon disulfide for wireworms, and Lange (1945, 1947) reported that 25,000 acres were fumigated for wireworms and nematodes with either D-D or ethylene dibromide before planting the bean crop. D-D is said to have given outstanding results in the Salinas Valley on fall lettuce when used at 400 pounds per acre, particularly when 35 pounds of anhydrous ammonia were applied with it to counteract the depressing effect on growth. Cook (1949) found D-D more efficient than ethylene dibromide or dichloronitroethane in compact soil. The penetrating power of D-D makes it more suitable for heavy soils than other fumigants and may explain why a 25-gallon rate per acre has worked better on sugar beet nematode-infested soil in Utah and Idaho, where soil types are heavier, than in California (Allen and Raski, 1950).

The question of residual effect or harmful accumulation from repeated annual applications is currently receiving attention. McBeth (1951) found no evidence of residue toxic to tomato, tobacco, melon or cowpea from five annual applications of 400 pounds of D-D per acre. A similar report by Ellis et al. (1949) indicates no cumulative toxicity from three annual applications of D-D, ethylene dibromide, chloropicrin or ethylene chlorobromide.

Some failures have been reported from the use of D-D for nematodes, but most of these are in connection with cyst-forming species, such as *Heterodera rostochiensis*. Peters and Fenwick (1949) reported only a 50 per cent reduction by applications as high as 800 pounds in certain English soils. The kill was improved by covering with sisalkraft paper and once by rolling. In the Isle of Jersey applications of 450 pounds per acre failed to reduce eelworm population, although yields of potatoes were increased somewhat, according to Small et al. (1950). On Long Island, Mai (1950) reported that two annual fall applications of 250 pounds of D-D reduced the population of viable cysts from 19 per ounce to 0.04 per ounce of soil. This, however, was not complete eradication

and so was unacceptable. Under some conditions considerable weed control has been obtained at dosage rates employed for nematodes and wireworms, but this can not always be counted on. It seems to be dependent upon the moisture content of the seeds. If they are about to germinate, kill is better than when they are relatively dry and dormant (Carter, 1945; Newhall and Lear, 1948).

ETHYLENE DIBROMIDE

Like D-D mixture and closely following its introduction, ethylene dibromide has had a meteoric rise as a very popular and useful soil fumigant, chiefly against wireworms and nematodes (Anon., 1946*b*). It might have come into use sooner had it not all been consumed during World War II in the making of tetra-lead-ethyl anti-knock adjuvant for aviation and other gasolines. First found by Lange (1946, 1947) and Cook (1949) to be very effective in California and Washington against wireworms, ethylene dibromide was soon shown by Christie (1947), Newhall and Lear (1948*b*) and many others to be a very potent nematocide (Townsend, 1948; Leding, 1950; Strand, 1951; Miller, 1951; Curzon, 1951; Lembright, 1953; Henry, 1953). After 60 experiments involving 50 fumigants, Lear (1951) concluded that, on a volume basis, ethylene dibromide was the most powerful nematocide of all, though closely followed by D-D and methyl bromide solutions. Many reports from the use of this fumigant on tobacco, carrots, celery, cotton, beans, beets, sweet potatoes and tomatoes have been summarized by Biron (1951). In California, only a few years ago, many thousands of acres were fumigated for wireworms. Recent use of Chlordane, Heptochlor and Aldrin, however, constitute much cheaper methods of control that have largely replaced D-D and EDB (Lange, 1947; Wellman, 1948).

Ethylene dibromide, like D-D, has a high boiling point. It needs no sealing in and so is adapted to extensive field applications. It has been marketed as a solution of various concentrations in a naphtha thinner at strengths varying from 10 to 85 per cent active ingredient (Anon., 1949). When the more concentrated solutions, 85 per cent, are employed, only four to six and one-half gallons an acre are needed. Side dressings of sugar beets in California, and pineapples in Hawaii with two, three and four gallons per acre have increased the tonnage and sucrose content. Use of ethylene

dibromide has become standard practice with many tobacco growers in Florida and Georgia, and on shade tobacco in Connecticut.

Ethylene dibromide is acknowledged by nearly all who have tested it as being very low in fungicidal activity (Schmitt, 1949; Jacks and Smith, 1952; Zentmyer and Klotz, 1949; Zentmyer and Kendrick, 1949; Wensley, 1953). However, a surprising and valuable discovery, reported by several workers the past few years, is the remarkable control of fungous diseases or root disease complexes obtained with this fumigant. Thus Smith (1948) and Presley (1950) obtained control of cotton wilt, induced by *Fusarium vasinfectum;* Meuli and Swezey (1949) of sweet potato black rot, caused by *Ceratostomella fimbriata.* A southern pine seedling root rot complex was controlled by Henry (1950, 1953). Koch and Stover (1950) and Jenkins (1948) controlled a brown root rot of tobacco, and Middleton et al. (1949) reduced losses from root rots on beans. Nusbaum and Chapin (1952) reduced black shank of tobacco, and Townsend (1948) controlled root rot in celery seed beds. It is believed by many of these workers that the benefits of fumigation with ethylene dibromide are indirect, being due to death of the nematodes or wireworms that are thought to be responsible for opening the way for certain parasitic fungi, some of which may be too weak to initiate infection by themselves. This and other observations by Christie (1953), Steiner (1945, 1949, 1953), Oostenbrink and Besemer (1953) and others to the effect that many soil-inhabiting nematodes are constantly doing more harm than hitherto believed possible, particularly the root lesion, sting, stubby root and meadow nematodes, which are widely distributed and harmful to a large variety of crops, all emphasize the importance and value of soil fumigation to agriculture in general. These observations should encourage its use, at least on a trial basis, in all sorts of disease situations where poor growth, slow decline or an unhealthy condition of obscure etiology exists. They scarcely warrant the wholesale propagation, however, of the doctrine that all fields of everything should be fumigated annually as a general sanitary measure. Treatment for wireworms with a three-year life cycle should not be required as often as for root knot nematode with a four- to six-weeks cycle.

The tobacco crop of the United States grown on the same soil for many years in a warm climate, and therefore subject to the ills

that nearly always follow a continuous cropping system, is probably gaining most from soil fumigation. All tobacco farms in North Carolina are said to be infested with nematodes, and the loss in 1952 was $25 million, according to Garris (1953). Here is where most of the D-D and ethylene dibromide are being used, nearly 100 thousand acres being fumigated in this one State in 1953. The question of which fumigant adversely affects the burning qualities of the cured leaf on account of its higher chloride content is a hot one (Anderson and Swanback, 1950; Kincaid, 1948). The delay in nitrification (Tam, 1945) brought on by the soil treatment is thought by Kincaid (1947) to be beneficial to shade tobacco.

Incorporation of ethylene dibromide in capsules was described by Lear (1951). The idea was so intriguing that one company bought a million of them before it was found that in field practice they do not all dissolve at the same time, which may result in crop injury later on, a phenomenon encountered 60 years earlier in the use of carbon disulfide against Phylloxera.

METHYL BROMIDE

The use of methyl bromide as a space fumigant in vaults and greenhouses preceded its use as a soil fumigant. In summarizing such work, Richardson and Johnson (1935) pointed out that it penetrates soil in a matter of hours, to kill insects and nematodes. Experiments soon followed to determine the proper dosage rates against a variety of pests, the extent of its phytotoxicity, and the best means of handling this odorless, colorless gas with its very low boiling point (4.6° C). At ordinary temperatures it must be dispensed as a vapor from sealed containers, such as steel cylinders or one-pound cans, or else it must be first dissolved, up to 15 per cent, in a cheap solvent such as propylene dichloride, carbon tetrachloride or xylene. The resulting solution can then be poured or injected into the soil. With the coming of gas-proof plastic tarpaulins of 100-foot lengths and up to 16-foot widths, seed beds, hot beds and bench soils can now be gassed under cover for periods of 24 to 48 hours at dosages of one to three pounds to the hundred square feet (Taylor and McBeth, 1940; Hamilton, 1940; English, 1944); Taylor and McBeth, 1941; Taylor, 1941; Gingrich and Haenseler, 1941; Godfrey and Young, 1943; Stark, Lear and

Newhall, 1944; Start and Lear, 1947; Koch, 1951; Magie, 1952; Marvel, 1953; Munnecke and Ferguson, 1953).

For ground beds and for small amounts of soil in covered garbage cans or steel drums, injections of small quantities of the liquid solution (" Bromex ", " MBX ") have found favor with florists. The dosage required for nematodes is phenomenally small, but to kill fungi requires one and one-half to two and one-half ml. of the pure methyl bromide, or its equivalent in solution, per cubic foot of soil, or about the same dosage rate as for chloropicrin (Newhall and Lear, 1948*a*, *b*; Leonard and Harris, 1950; Anderson and Swanback, 1951; Gruenhagen, 1953).

Several thousand acres of seed beds devoted to tobacco in the United States are now fumigated with methyl bromide, according to Koch (1951) and to Freeman (1948). Of 12 chemicals compared, Hill et al. (1951) found methyl bromide the best weed killer for tobacco beds, the others being more or less selective. The cost of fumigation with methyl bromide is not quite so high as with chloropicrin but still is too high to give it a place on land growing low value crops. The necessity of sealing it in with gas-proof tarpaulin, asphalt coated paper or a sprinkling of water adds to its inconvenience in large areas out-of-doors. However, Kopitke (1951) reports seven acres of tree nursery profitably fumigated under tarpaulins over a three-year period at $325 an acre per year with an annual saving of $550 of weeding cost; besides much better stands, faster growth and sturdier seedlings resulted. Legume seeds are the hardest to kill. In general, as a nursery seed-bed treatment, fumigation with methyl bromide has become exceedingly popular (Dieter and Coulter, 1949; Leonard and Harris, 1950; Hill, Klingman and Woltz, 1951; Stover and Koch, 1952; Swank and Perry, 1953).

The advantages possessed by methyl bromide over other soil fumigants are its fast penetrating ability, making it unnecessary to wait for root knot nematode galls to rot in the soil; the speed with which it leaves the soil; and its low phytotoxicity, making it possible to treat soil in close proximity to growing plants and at lower temperatures than with other fumigants (Stark et al., 1944; Stark and Lear, 1947; Lear, 1951). Some greenhouse growers, recognizing the better fungicidal properties of chloropicrin, use it in the summer when soil temperatures are highest, and methyl

bromide in the winter when soil temperatures are low and time is short.

Daily fumigation of 300 to 500 flats of soil under a plastic tarpaulin is said to be common practice in certain California nurseries where four pounds to 100 cubic feet of space is used and the gas is passed through a copper tube immersed in water at 160° F to insure rapid volatization. Several of the worst sclerotia-forming soil fungi are controlled in this way, according to Munnecke and Ferguson (1953).

The problem of exterminating poultry parasites from the soil in poultry ranges is receiving some attention, according to Clapham (1950) who was successful in killing ova, in soil, of *Ascaridia lineata, Heterakis gallinae* and *Syngamus trachea,* in both freshly passed and embryonated states.

Cut ants were successfully eradicated in Texas by the liberation of a pound of methyl bromide in each of the burrows, according to Kennerly (1953).

Addition of alcohol to methyl bromide reduced its efficacy against the root knot nematode very much, according to Gingrich and Haenseler (1941).

Adsorption of methyl bromide, like that of chloropicrin, may take place on certain soils. The chief factors determining this are soil type and moisture content. Dry peat adsorbed 41 per cent of a given charge but wet peat only 20 per cent, according to Chisholm and Koblitsky (1943) who likewise found that wet and dry clay adsorbed 25 and 11 per cent, respectively, while sand adsorbed less than ten per cent, wet or dry. On the other hand, Fuhr, Bransford and Silver (1948) found a sandy clay soil with 11 per cent moisture to adsorb little or no methyl bromide, even though the same soil adsorbed hydrogen sulfide, hydrogen cyanide and sulfur dioxide to a marked extent. Relatively poor control of root knot nematode was obtained with a given dosage by Lear (1951) in a muck soil as compared to that in a sandy or clay soil. Others had reported poorer kill of bacteria and fungi in organic soils, the moisture content being of less mportance than the organic content (Dieter and Coulter, 1949; Wensley, 1953).

There are a few cases on record of apparent injury to certain plants grown in methyl bromide-fumigated soil. This was thought by Williamson (1953) to be due to adsorption of bromine by the

organic or the colloidal clay fractions of certain heavy soils. Plants particularly sensitive to bromine were chrysanthemum, carnation, viola and salvia. The retarding effect sometimes lasted several weeks. One variety of chrysanthemum out of 11 exposed to the fumes above ground was found exceedingly susceptible by Newhall (1951, 1952), indicating a striking varietal difference in subsceptibility.

Regardless of isolated cases of injury from fumigation with methyl bromide, the ease with which it can be handled and its efficiency against a wide variety of pests assure it an important place in the pharmacopoeia of agricultural chemicals.

An attempt to kill the root rot fungus, *Phytophthora cinnamomi,* under living avocado trees by fumigating with methyl bromide or chloropicrin, or by treatment with Vancide 51 or Dithane D 14 resulted in too much tree injury for treatments to be recommendable, according to Gustafson (1954).

FORMALDEHYDE

For many years formaldehyde has been used as a seed, soil and space disinfectant. Its precarious claim to a place among soil fumigants emanates from its use by Sayre and Thomas as a dust for controlling smut of cereals. Others have employed it for soil treatment as a six per cent dust adsorbed on some inert carrier such as charcoal, infusorial earth, ground oat hulls, sawdust or even dry muck soil. Rates of application per bushel of soil varied from six to 16 ounces of a dust containing about 15 per cent formalin, dry weight basis (Wilson, 1930, 1932; Wilson and Tilford, 1933; Alexander et al., 1931; Tilford, 1931, 1932; Brown, 1941). The mixing process with the soil was rather disagreeable, and proprietary preparations tended to deteriorate so that the use of formaldehyde dusts for soil disinfestation enjoyed but short popularity. Some workers found the results with it somewhat inconsistent (Person, 1939; Person and Chilton, 1942).

An essentially similar method of dispensing formaldehyde in fairly concentrated form for damping-off control was developed by Guterman and Massey (1935). They employed a very small amount of water in place of the dust as a carrier and emphasized thorough mixing with the soil. Both methods reduced the time interval between treatment and planting from ten days in the old drench method to 24 or 48 hours. For controlling damping-off in

seedbeds it was found that sprinkling the beds with a dilute formaldehyde solution, 1–200 to 1–600, immediately after sowing the seed was very effective in improving the emergence of many different seeds (Haenseler, 1935; Ogilvie et al., 1938; Anderson and Swanback, 1951).

Eradication of root-rotting organisms and nematodes deep in the soil has been attempted in connection with the root rot of cotton and of date palm in California (McKinnon and Lillelund, 1931; Kellerman, 1932; King and Hope, 1932). The latter employed a gallon per cubic foot of a one and one-fourth per cent solution under pressure with special apparatus which forced the solution into the soil as far as six feet. With injections a foot part, five acres required almost one and one-third million gallons of solution (Skillman, 1949).

Addition of formaldehyde to steam and to carbon disulfide emulsions to increase the speed of action and range of lethal effect has already been mentioned (Winston, 1913; Guba, 1932; Beachley, 1937; Hunt et al., 1925; Manns, 1947). The cost and bother of applying formaldehyde, either as a drench or by one of the methods requiring mechanical mixing with the soil, and the fact that it is not a very good nematocide have all militated against its extensive use, even in greenhouses. Attempts to reduce the cost somewhat were made in 1928 and 1932 by Doran who substituted acetic or pyroligneous acids for the formaldehyde, and by Bewley in 1935 who substituted crecylic or crude carbolic acid, but none of these is cheap enough or effective enough to win favor with practical growers. Jacks (1948) compared formaldehyde in an 0.8 per cent solution with paraform against Verticillium wilt of tomato and concluded that paraform was milder in both fungicidal and phytotoxic effects. Formaldehyde persisted longer. One of the most successful applications of formaldehyde against a fungous disease is its use in the control of onion smut. A very dilute solution, 1–128, when dribbled into the row, at the time of sowing the seed, at the rate of about 110 gallons to six or seven miles of row, gives almost perfect control of this disease (Walker, 1920; Anderson, 1923; Nelson, 1948).

MISCELLANEOUS FUMIGANTS

To name all the fumigants that have not quite come up to requirements for successful adoption is unnecessary, but some may

deserve mention as not having yet been thoroughly enough tried to fall in the hopeless group. Thus the tetra and penta chloroethanes were found by Godfrey and Young (1943) and by Stark and Lear (1947) to be potent nematocides. Also dichlorisopropyl ether was very effective. But these persist too long in the soil and are too phytocidal to seem very promising.

Allyl alcohol and allyl bromide have been shown to have fungicidal properties that can not be lightly dismissed, the latter being one of the best of 14 tested by Christie (1945, 1947) against root-knot nematode and several soil fungi. Allyl bromide was found to compare favorably with chloropicrin against Verticillium wilt of tomato, although it failed to diffuse upward as well, according to Schmitt (1949) and Wilhelm and Ferguson (1953).

A mixture of chlorinated and brominated hydrocarbons containing over 55 per cent chlorobromopropene has recently shown marked soil-fumigating properties against a variety of soil fungi as well as nematodes (Kreutzer and Montagne, 1950; Haasis, 1952). It needs no seal but is a disagreeable, rather phytotoxic lachrymator, the cost of which may limit its use, like chloropicrin. It was sprayed in the row at the time of sowing to control pea and bean Fusarium root rot by Watson (1951).

Since the preliminary testing of dichlorobromopropene by Christie, who found it rather effective against nematodes, Lear (1950) found it as good as D-D mixture against the golden nematode of potato, although it persisted longer in the soil.

Dibromobutene, another lachrymator with low vapor pressure, has been used in solid form as a dust incorporated with the soil for celery seedbeds and greenhouses where it has shown promise against a variety of soil fungi, according to Kreutzer et al. (1951) and to Swank (1951). Though volatile, it needs no seal. It was one of the four better fumigants compared in the field against the golden nematode when used in two split applications at 225 pounds each (Lear, 1950; Lear et al., 1952). But being more phytotoxic, disagreeable and expensive than D-D, its future seems somewhat doubtful at present.

Parathion is not ordinarily used as a fumigant and may not have acted in this way in an experiment by Dimock and Lear (1950), in which root-knot nematode was controlled by one gram of 15 per cent wettable powder mixed with a gallon of soil in which

susceptible plants were subsequently grown. The plants may have absorbed the chemical and become immune. This rate is over 30 times the normal one per acre. A dose 50 per cent larger killed *Heterodera rostochiensis,* the golden nematode of potato, while chlordane and benzene hexachloride failed even at larger dosages. Clayton and Ellis (1947) found benzene hexachloride unable to control root-knot, even at 675 pounds per acre where it became very phytotoxic.

Among the more interesting fumigants tested against the cysts of the potato golden nematode are the ammonium and calcium chloroacetates and the isothiocyanates, one of which, allyl isothiocyanate, is mustard oil, reported on by Smedley (1938, 1939) and Ellenby (1945, 1947). While these chemicals brought about yield increases, they never reduced the nematode population sufficiently to be recommendable. In fact, nothing has thus far appeared recommendable as an eradicant against this nematode, according to Chitwood and Buhrer (1945) who summarize five years work with fumigants on Long Island by saying that, although in some instances over 90 per cent control was obtained with D-D mixture, carbon disulfide, chloropicrin or methyl bromide, nevertheless, yield increases of potatoes covered the cost of treatment in only three out of five cases where D-D was used, three out of seven where carbon disulfide was used, four out of 25 where methyl bromide, and none out of seven where chloropicrin was used.

When 600 soil fumigants were tested against six common soil pathogenic fungi by Schmitt (1949), the following were lethal: allyl bromide at 61 gallons per acre; allyl and ethyl isothiocyanate at 76; formalin, Iscobrome and D-D at 380; allyl chloride and methyl bromoacetate at 456 gallons. Chloropicrin was the most effective, killing all fungi at 8.6 gallons.

DEVELOPMENT OF FUMIGANT DISPENSERS

The development of adequate machinery for accurately dispensing soil fumigants soon followed the discovery of the remarkable virtues of chloropicrin. Here the European experience with carbon disulfide dispensers, at the close of the last century, was very helpful (Vermorel and Crolas, 1915). The French "Pal"

by Vermorel was imitated and improved by several manufacturers who brought out the " Carbona prod ", the " Calispray ", the Innis Speiden 4 models of " Larvajector ", the Mack " Anti-Weed Gun " fumigator injector, and the McLean fumigator hand injector (Godfrey and Young, 1938; Jacks and Wright, 1947). Multiple-row, continuous-flow, sub-surface injectors and gravity flow as well as forced feed sprayers for plow applicators have been developed by the dozen and are described or illustrated by Johnson (1935), Neller and Allison (1935), Godfrey and Young (1943), Carter (1945), Newhall (1946), Cook and Lane (1947), Walter and Kelsheimer (1949), Clark and Myers (1951), Watson (1951) and Jacks (1952). Some of the more recent models are pictured anonymously in Down to Earth (1947) and Farm Management (1953). Jenson (1953) found that power-drawn equipment failed to duplicate results obtained with hand gun. Piston type pumps actuated by a cam on a spiked auxiliary wheel off to the side of the plow (Hasson, 1920; Starnes et al., 1951; Jacks, 1952) have given way nearly everywhere to inexpensive gear pumps that maintain a steady pressure of 20–30 lbs. on one to ten lines of fumigant. The fumigant is sprayed on to the plow sole or is forced through copper tubes behind a series of spear shanks drawn through the soil by a tractor at a constant speed (Newhall and Lear, 1948; Lear, Mai, Feldmesser and Spruyt, 1952). In one inexpensive outfit for cotton the fumigating, fertilizing and bedding or " boarding off " are all done in one operation (Kelsheimer and Walter, 1949), and in Hawaii a number of operations, as land fitting, fertilizing, fumigating and mulch paper-laying, are done at one time (Nelson, 1951).

It is the careful refinement of this fumigation equipment that has permitted accurate employment of more and more concentrated fumigants at reduced amounts per acre. As little as six or even three gallons of an 85% ethylene dibromide solution are sometimes used (Kay, 1951; Lembright, 1953). At such rates there is a saving of weight, of labor, of shipping charges and of storage space (Biron, 1951). Compact fumigation kits are now available to farmers, ready to be attached to their tractors. The remarkable development of such equipment has had much to do with the fact that 200 to 300 thousand acres of farm land were probably fumigated in the United States in 1953.

CHEMICAL AND BIOLOGICAL CHANGES INDUCED BY SOIL DISINFESTATION

The main purpose of soil disinfestation has always been to kill detrimental microflora and to control weed seeds, although it has not always been expressed as bluntly as this. In the search for an explanation of the remarkable increases in plant growth following soil treatments with heat or fumigants, chemists, bacteriologists, agronomists, plant physiologists and biologists have propounded a number of ingenious theories. These have been well reviewed by Schreiner, Oswald and Lathrop (1912), by DuBuisson (1917) and by Kopeloff and Coleman (1917). These theories need no further elaboration. Many of the older investigators have expressed a touching concern for the useful microorganisms that must inevitably suffer the same fate as their parasitic relatives in any effective soil treatment. Some workers seemed bent on explaining crop responses to soil treatments the hardest way possible. However, we are indebted to them for a number of well established facts.

Treating soils, either by heat or by " antiseptics ", has the following results:

(*a*) Non-spore-forming, nitrogen-fixing, nitrite-forming and nitrate-forming bacteria, as well as parasitic organisms are destroyed, and nitrification is thereby inhibited. The spore-forming ammonifiers which escape, therefore, have a field day, and ammonification goes on almost uninterrupted for weeks, especially in soils high in organic matter.

(*b*) Soluble salts are often liberated by heat in quantities two to ten times their previous level, being in some cases chlorides and sulfates of ammonia and sometimes soluble manganese (Gregory, 1936; Hoffman, 1939).

(*c*) Treated soils often have a reduced capillarity and water-holding capacity resulting from destruction of some colloids (Smith, 1926; Malowany and Newton, 1947).

(*d*) The steaming of some soils makes available more calcium, potassium, phosphorus, zinc, copper and nitrogen, according to Milliken (1942). Bad effects, which sometimes result from soil treatment, can not be attributed to this greater availability of these elements nor to that of aluminum, ammonium, iron or total salts, according to Robinson (1944).

Recent work has added many refinements to our basic knowledge but has also raised inadequately answered questions, some of which are related to the fact that soils rich in organic matter are very heavily populated with microorganisms. Thus in a study of the effect of steaming four different Canadian soils, Malowany and Newton (1947) found that soluble phosphates and sulfates increased by one-third in soils rich in organic matter. Capillary activity was reduced in all. No change in pH occurred, nor was there a change in particle size detected by mechanical separation. While steaming does not change the pH of the soil, the microflora that builds up after steaming an acid soil may be quite different from that which follows treatment of an alkaline soil, according to Herzog (1939) and Walker and Thompson (1949). Steaming a moist alkaline soil results in greater ammonia accumulation than a dry acid soil, which is probably the reason why adding lime to some soils before steaming may be detrimental (Walker and Thompson, 1949). Gypsum is much better, according to Hoffman (1939). Some soils contain replaceable manganese, and when other salts are present in abundance, steaming, particularly acid soils, may result in the accumulation of excessive amounts of water-soluble manganese, which is phytotoxic (McCool, 1934). Addition of lime to acid soils before steaming reduces the danger of toxicity from soluble manganese but induces faster ammonification. Addition of commercial fertilizers containing phosphates, particularly gypsum, reduces phytotoxicity from accumulations of both manganese and ammonium salts.

The microflora that follows steaming varies qualitatively and quantitatively for different soils, but *Trichoderma* seems to be one of the first to reenter and build up. Ludwig and Henry (1943) attribute to the activity of this fungus the unique fact that when *Ophiobolus* is reintroduced into steamed soil, it is less virulent than when introduced into non-steamed soil. Tam and Clark (1943) found that steam alone, chloropicrin or formaldehyde, or steam in combination with chloropicrin or formaldehyde eliminated nearly all the fungi except *Trichoderma* in a pineapple soil of Hawaii. Six weeks later a large population of both bacteria and Actinomycetes had developed in the soil. That some Actinomycetes can withstand steaming for many hours was shown by Kurzweil (1943). All the fumigants used by Tam and Clark inhibited

nitrification, and ammonia accumulated in proportion to the efficiency of the fumigant at killing the nitrifiers. Nitrification was repressed longer by steam than by chloropicrin and least by formaldehyde.

That annual treatments of soil have little permanent effect in altering the microflora is indicated by the study of Cohen (1950) on the effect of burning over and grazing the veld of South Africa. Seven years of burning did not result in a change or in the establishment of a distinct soil flora, though others have shown that cultural practices could do just this.

The delicate balance between nutrients and antibiotics that may exist in a given soil is illustrated by the work of Lambert and Humfeld (1939) who found that heating certain mushroom-casing soils, if the temperature goes over 135° F, may cause a reduction in the mushroom yields by 50 per cent. A somewhat similar situation was described by Lawrence and Newell (1936), where steaming a compost soil for 30 minutes caused retarded growth of *Primula simensis,* but steaming the peat, sand and loam ingredients of the compost individually before mixing, relieved the situation. However, Grooshevoy and Levykh (1936) obtained better results by mixing compost ingredients together before steaming. That there may be several types of injury resulting from heating of soil is indicated by Bewley (1950) who states that the control for one kind of injury may be flooding; for another, adding phosphate; and for a third, addition of horse manure. The first would eliminate excess soluble salts and organic matter; the second would presumably react and prevent accumulation of excess manganese; while the last would quickly alter biotic relationships and hasten the break-down of organic toxins.

In a comparison between steam and formaldehyde treatments, which, however, were not carried out to similar depths, made in a 25-year-old forestry nursery of high pH, Warcup (1951) found that more fungi recolonized the steamed soil and that fewer species recolonized the formaldehyde soil. The dominant recolonizer in the formaldehyde-treated soil was *Trichoderma virida;* in the steamed soil *Mortierella, Phoma* and *Coniothyrium* were prevalent. *Pythium* was recovered from both soils 13 weeks after treatment, and by the third year it was an abundant as ever in the steamed.

Work at the Pennsylvania Pasture Research Laboratory showed that the adverse growth effects of heating a soil are products of time and temperature. A few days at a temperature of 50° C produced the same toxic effect that two hours at five pounds steam pressure did (105° C?). The toxic effects were counteracted by applying an abundance of phosphate either before or after steaming, but were also removed by adding untreated soil to the steamed soil, according to Robinson (1944). In this connection the work of Winter is of interest. He found the runners of *Ophiobolus graminis* to be stimulated by treatment either with steam or with volatile fumigants, a fact he explained as due to the destruction of inhibitory factors by the soil treatment. These factors were restored by adding untreated soil, provided this was of a type similar to the original soil. The inhibitory substance produced by the microflora of one soil may be quite different from that of another. Thus a heath humus was very effective, while a loess was not. The complexity of these biotic factors is further indicated by the work of Meredith (1944) who, in a study of 66 soil samples in Jamaica, found 17 organisms out of 128 isolated that were able to retard the growth of *Fusarium oxysporum* in soil solution agar cultures. However, some of these were unable to retard this fungus if transferred to soil solution cultures prepared from other soil samples than the one they originally came from. Just what are these inhibitors?

Since fumigation is performed at ordinary soil temperatures and, therefore, does not break down organic matter and liberate soluble salts to the extent that steaming does, we can expect fewer toxins to be produced by soil fumigation, other than the lingering of the fumigant itself. Few people adhere to the dogma that fumigation benefits are attributable to chemical changes in the soil. Most investigators credit the value of soil fumigation to suppression of disease-inciting organisms. However, the biotic balance may be upset by fumigants almost to the same extent that it is by steam. In all cases nitrification is inhibited and ammonification accelerated. Thus Kincaid and Volk (1949) found a prolonged retention of ammonia in Florida soils fumigated in September, December and February with D-D and with ethylene dibromide. This extended into April with ethylene dibromide and into May with D-D mixture.

There is considerable specificity exhibited by some fumigants against certain nematodes. For example, Graham and Holdman (1953) report only half as many meadow nematodes (*Pratylenchus*) killed by a dose of ethylene dibromide which killed all the sting nematodes (*Belonolaimus*). Ethylene dibromide is believed by Gerald Thorne to be much more specific than D-D against the potato rot nematode (*Ditylenchus destructor*), while D-D mixture has been found much more effective against the golden nematode on Long Island, according to Lear et al. (1952). The resistance of the cyst stage of any nematode is greater than that of the egg, and of the half grown larvae than that of the mature larvae. So after a job of fumigation, if the full grown larvae of saprophagous nematodes are still found, it is pretty certain that the more resistant egg stages of parasitic nematodes have survived the treatment. Similarly, of 10 or 12 important soil fungi, the Pythiums and the Phytophthoras are much more susceptible to fumigants in general, and those with mild fungicidal properties in particular, than are, for example, the Fusaria (Zentmyer and Kendrick, 1949). The sclerotia of most fungi are harder to kill than the vegetative stages, especially when they are dry, but *Streptomyces ipomoea* was not controlled by dosages of D-D that did control *Sclerotium rolfsii* in Louisana (Martin, 1953).

We are still using the Edisonian method of testing soil fumigants and are very much in the empirical stage of correlating fumigation capacity with chemical constitution or molecular configuration. To some extent the toxicity of a homologous series of compounds is directly related to the boiling point, but, on the other hand, toxicity is also related to volatility in many cases; sometimes it may be the toxicity of the substituted radical used in raising the boiling point that is responsible for the effect. In general, the halogen radicals seem to be more fungicidal than the nitro, amino or alkyl substituents, according to Beraha and Powell (1953). With insects, which must respire to take up the fumigant, inherent toxicity as well as volatility are important. It is significant that chloropicrin, which boils at 112° C, is so much more toxic per unit than carbon disulfide, which boils at 46° C, that it is a superior soil fumigant. The work of Lehman (1942) is of special interest here. He tested 114 compounds and determined the median lethal concentration of 57 for wireworm control under

laboratory conditions. Of nine compounds which were more effective than carbon disulfide in the air, only three were more toxic than carbon disulfide in soil, and the relative toxicity of all substances was reduced in contact with soil, presumably by adsorption of the gases. The rate and extent of diffusion may be very important because chloropicrin, which in these laboratory tests was 14 times as toxic as carbon disulfide in air, was only three times as effective in the field. Similarly allyl isothiocyanate, which was 29 times as toxic in air, was just equal to carbon disulfide in field tests. The more rapid diffusion and lower adsorption of carbon disulfide are assumed to be responsible for its better showing in these cases.

Besides toxicity to the pathogen, phytotoxicity must be considered in evaluating a soil fumigant. Three factors are important here: the vapor pressure, the amount required to kill the pathogen, and the concentration tolerated by the host plant. Since volatility is negatively correlated with boiling point, the latter is a good criterion of the behavior of a fumigant with respect to the need for sealing it in and to the time required to get rid of it again. Fumigants that boil between 40° and 100° C will doubtless need a seal of some kind to permit building up to lethal concentration in the top two inches of the soil, but will escape rapidly. Those boiling between 100° and 120° C will not persist too long and may not need much sealing, while those boiling at 130° to 140° C need no seal as a rule, but may persist a little too long sometimes (Stark and Lear, 1947). Fumigants with extreme toxicity may be used at such low dosage rates as to offset their undesirable persistence. Ethylene dibromide falls in this class. It is even being used as a side dressing along the row against nematodes on pineapple and even beets (Curzon, 1951). Weak toxicants like xylene, on the other hand, even though of a low order of phytotoxicity, have to be used at such high dosage rates as to require long aeration periods. A product like methyl bromide is of special value for having high toxicity, low phytotoxicity and a high volatility, thus saving growers much time. But when cost also enters the picture, the ideal soil fumigant has not been found yet (Newhall, 1946). It should be highly toxic to a wide variety of pests but not too phytocidal or too persistent. It should be inexpensive, stable and not too disagreeable to handle or too hard on the equipment. No

wonder we are settling for a number of different fumigants, each with but a few of these qualities.

SUMMARY

The primary object of soil treatment, whether by heat or by volatile chemicals, is to kill pathogenic microorganisms, although many scientists at the beginning of this century were inclined to explain favorable plant responses chiefly on the basis of chemical changes and increased fertility.

In parts of the world the heat of the sun kills some pathogens, particularly root-infesting nematodes, the thermal death points of which are low. Surface burning and roasting of seedbed soils have been practiced for nearly a century and may have been common in ancient times.

Steaming is more effective than drenching with hot water, and has reached its highest state of development in greenhouses of the north temperate zone. A number of ingenious ways have been developed by growers to conduct steam to the soil. Among these are the buried perforated pipe, the buried tile, the inverted pan and the steam rake. A modification of the pan system, called the "surface system", was found to work at low steam pressures. The relative costs of labor versus equipment usually determine which system a greenhouse grower adopts. The amount of coal required to steam an acre is in the neighborhood of 40 tons. The so-called merits of high pressure steam versus low, and of long time steaming versus quick pasteurization, are exploded myths. Less injury to rich soils is likely from the latter.

Electricity has been used to heat soil in two ways, one a direct heating system in which the current passes through the soil between two or more vertical or horizontal electrodes, the other an indirect process in which heat is imparted to the soil by thermal conductance from buried heating elements of uniform fixed capacity. Each has its good and bad points, but electric pasteurization is limited by the relatively small amount of current available to growers at any one time.

Flood-fallowing has specialized uses against some insects and fungi but requires such a long time and is available to so few growers that its adoption is restricted to a few special locations, as in delta regions.

Soil fumigation is one of the oldest and newest ways of successfully fighting soil pests. It reached a high state of development in Europe near the close of the last century where carbon disulfide was used on hundreds of thousands of acres in the fight against the Phylloxera of grape. After the first World War the merits of the war gas chloropicrin revived interest in this method. Other volatile fumigants began pouring from the organic chemical laboratories, and it has now become profitable to treat two or three hundred thousand acres of farm land devoted to tobacco, vegetables, pineapple and ornamentals in the United States.

The four most popular soil fumigants are ethylene dibromide, the dichloropropene-propane mixture known as D-D, chloropicrin and methyl bromide. Each has its place, but none is ideal. The least expensive are good, chiefly against nematodes and insects, while those with fungicidal properties, in addition, are more expensive. A number of others have not been quite good enough to gain great popularity.

The advantages from soil fumigation have been made possible through the development of inexpensive equipment for accurately dispensing metered amounts of the fumigants, often as little as three gallons an acre. Tractor-drawn equipment capable of doing many acres a day is now available.

Reducing losses from several root rot complexes by treatment with nematocidal and insecticidal fumigants has awakened people to the importance and widespread occurrence of many root-feeding nematodes and wireworms which help initiate fungus rots.

Formaldehyde has been used as a drench, a dust and a concentrate, and for small quantities of soil is very useful against fungus pathogens.

With the manufacture of over 1000 new organic chemicals a year by each of several manufacturers, there is every chance that some day better soil fumigants will be available. Several new ones are undergoing tests in various field laboratories all the time. We are still in the empirical stage of testing, although the boiling point is known to be important and the halogen substituents are more fungicidal than the nitro, amino or alkyl.

A good deal of specificity is known with respect to the toxicity of a given chemical for different organisms. The ideal soil fumigant is yet to be found.

Repeated annual fumigations have no deleterious cumulative effects over a five-year period, although temporary suppression of nitrification occurs for a few weeks as it does after steaming, with its attendant accumulation of ammonia.

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